

The MGDO software library for data analysis in Ge neutrinoless double-beta decay experiments

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Abstract. The GERDA and MAJORANA experiments will search for neutrinoless double-beta decay of ^{76}Ge using isotopically enriched high-purity germanium detectors. Although the experiments differ in conceptual design, they share many aspects in common, and in particular will employ similar data analysis techniques. The collaborations are jointly developing a C++ software library, MGDO, which contains a set of data objects and interfaces to encapsulate, store and manage physical quantities of interest, such as waveforms and high-purity germanium detector geometries. These data objects define a common format for persistent data, whether it is generated by Monte Carlo simulations or an experimental apparatus, to reduce code duplication and to ease the exchange of information between detector systems. MGDO also includes general-purpose analysis tools that can be used for the processing of measured or simulated digital signals. The MGDO design is based on the Object-Oriented programming paradigm and is very flexible, allowing for easy extension and customization of the components. The tools provided by the MGDO libraries are used by both GERDA and MAJORANA.

1. Introduction and requirements

The GERDA [1] and MAJORANA [2] experiments are designed to search for the neutrinoless double-beta ($\beta\beta$) decay of ^{76}Ge using isotopically-enriched high-purity germanium (HPGe) detectors. The experiments differ in basic approach and in the shielding philosophy for background suppression. Detectors in GERDA are directly immersed in liquid argon, which acts both as cooling medium and as passive shielding against external γ radiation. The commissioning of GERDA was successfully completed and the Phase I data taking has recently started with eight HPGe detectors enriched in ^{76}Ge (total mass of about 15 kg). The design adopted by MAJORANA consists in operating HPGe detectors in an ultra-radiopure vacuum cryostat surrounded by

passive lead shielding. The MAJORANA Collaboration is currently constructing two modules of HPGe detectors, with a total mass of about 40 kg of natural and enriched germanium, and is scheduled to begin data taking with the first module in 2013.

In spite of the different shielding design of the two experiments, they use many of the same materials and employ similar detector technologies. Since 2004, GERDA and MAJORANA have taken advantage of this overlap by collaborating in an open way on topics of common interest. In particular they jointly develop and maintain a common and flexible Monte Carlo framework, MAGE [3]. The advantage of having a shared software project is that it avoids duplication of effort for software tools of common interest, thus easing debugging and validation efforts. Following this experience, a new shared software project has been initiated by GERDA and MAJORANA called MAJORANA-GERDA Data Objects (MGDO). The core function of this software is to provide a collection of C++ objects to encapsulate HPGe detector array event data and related analytical quantities. MGDO thus provides a shared standard for the storage, access, and manipulation of GERDA and MAJORANA data. It also includes implementations of a number of general-purpose signal processing algorithms to support advanced detector signal analysis.

2. Basic concept and design

MGDO is designed as a set of class libraries exploiting the Object-Oriented paradigm. Virtual base classes are provided which define abstract interfaces. Such an approach makes the code flexible, easing future extensions and user customization. The source code is written in the C++ programming language, allowing for the interfacing and extension of MGDO with other general-purpose software for scientific computing. In particular, MGDO adopts the system of units, physical constants, and several other tools provided by the CLHEP libraries [4]. MGDO may also optionally be built against FFTW3 [5] for its fast digital Fourier-transform routines, and may be built against ROOT [6] for its advanced data storage and analysis tools.

The tools provided in MGDO can be divided in two main categories: data objects and transforms. The “data objects” are C++ classes which encapsulate complex data and physical quantities, for example digitized waveforms, detector parameters, and channel cross-talk matrices. The aim of the data objects is to support data management and handling: the existence of an MGDO-defined standardized format eases the exchange and the cross-comparison of information, for example between Monte Carlo simulations and experimental data, or between different detector systems. ROOT wrappers for the data objects are also provided, which makes possible the storage of MGDO data objects in a ROOT-based format. A concrete example of one of our key data objects, MGWaveform, is presented in section 3.

The other main category of tools provided by MGDO are “transforms”, general-purpose algorithms for digital signal processing. They encompass digital filters and other utilities, such as smoothing, differentiation and extremum finders. Fourier and wavelet transform routines are provided to enable analysis in the time domain, the frequency domain, or both. Having many commonly-used algorithms available avoids code duplication in experiment-specific analysis software, and thus enhances testing, validation and performance optimization. ROOT wrappers for transforms are also provided to enable their use in interactive ROOT sessions. Transforms are discussed in more detail in section 4.

3. A concrete data object: MGWaveform

One of the key data objects provided by MGDO is MGWaveform. It is designed to store and manipulate a digitized waveform produced by any kind of detector (an HPGe detector, a photomultiplier, etc.). At its heart, MGWaveform is simply an array containing the individual samples of the waveform, plus a number of auxiliary attributes such as the sampling frequency, a time value to associate with the start of the trace, and the waveform type (e.g. voltage pulse, current

pulse, etc.). The public interface of the class consists mostly of protected Get and Set methods for the attribute I/O, and of custom operators implementing widely-used waveform-waveform or waveform-scalar operations (product, sum, etc.). The definition of custom operators facilitates the basic handling of waveform by internally managing the loop over the individual samples and by providing a consistent output.

The “ROOTified” version of the class, MGTWaveform, has additional public methods which are inherited from the ROOT interface and provide direct connection to the ROOT I/O, graphical, and analytic utilities. For example, MGTWaveform provides functions to represent the waveform as a histogram object (TH1) that can be drawn or fit. It also provides methods to set a waveform from a function object (TF1), or to treat the waveform as a TF1 to be used itself as a fit function.

An advantage of MGWaveform is that it can be used as a standard output format. Experimental waveforms can be stored as MGWaveform objects, while the output of Monte Carlo simulations can be also directly produced as MGWaveforms. This allows the real and simulated waveforms to be treated on exactly the same footing by the analysis, easing inter-comparison, validation, adoption of simulated pulses into analysis routines, etc. Furthermore, having a common format facilitates the exchange of information between GERDA and MAJORANA, including data and Monte Carlo results of common interest.

Other data objects are available in MGDO, as for instance MGTEvent. MGTEvent is an MGDO class designed to encapsulate the full information of events: it includes a set of waveforms (one per channel) and additional data attributes, such as a time stamp and DAQ flags.

4. The transforms

The MGDO transforms are general-purpose algorithms for operations on MGWaveform data objects. The possible output of a transform is either a new MGWaveform (e.g. for filters or smoothers), or a set of scalar parameters (e.g. rise times or extrema), or both. Each transform is implemented as a class inherited from the general virtual class MGWaveformTransformer. The base class provides a general interface making it easy to add new user-specific transforms.

Implemented transforms that give a new waveform as output include ones which calculate and subtract a baseline, calculate the numeric derivative using simple (three-point) or more complex (five-point or RC derivative) algorithms, smooth the waveform using a moving average or triangular smoothing, and apply a trapezoidal filter [7]. Some of the scalar parameters calculated by transforms based on the input waveform(s) include the χ^2 difference of two waveforms, the global maximum or minimum of a waveform, and the rise time within given limits, e.g. 10% and 90% of the amplitude.

A complex digital analysis of a real-life experiment can be implemented as a chain of MGDO transforms, each performing a basic step of the processing. An example of chain, involving the smoothing and differentiation of a charge pulse, is depicted in Fig. 1.

5. Real-life application of MGDO

The tools available in the MGDO library are used in the analysis software under development by MAJORANA and GERDA. Both the GERDA analysis framework GELATIO [8] as well as the MAJORANA analysis toolkit “GAT” rely on MGDO for the I/O structure and for the basic digital filters used in signal processing. Raw data produced in the GERDA and MAJORANA apparatuses as well as in detector test stands and simulations are transformed in MGDO data objects and stored as ROOT files. This allows the treatment of all data with the same analysis framework, irrespective of the native DAQ binary format and of the type of detector. Digitized traces from both HPGe detectors and photo-multipliers (e.g. from veto detectors) are treated identically and are stored in arrays of MGWaveforms inside MGTEvent objects. Furthermore,

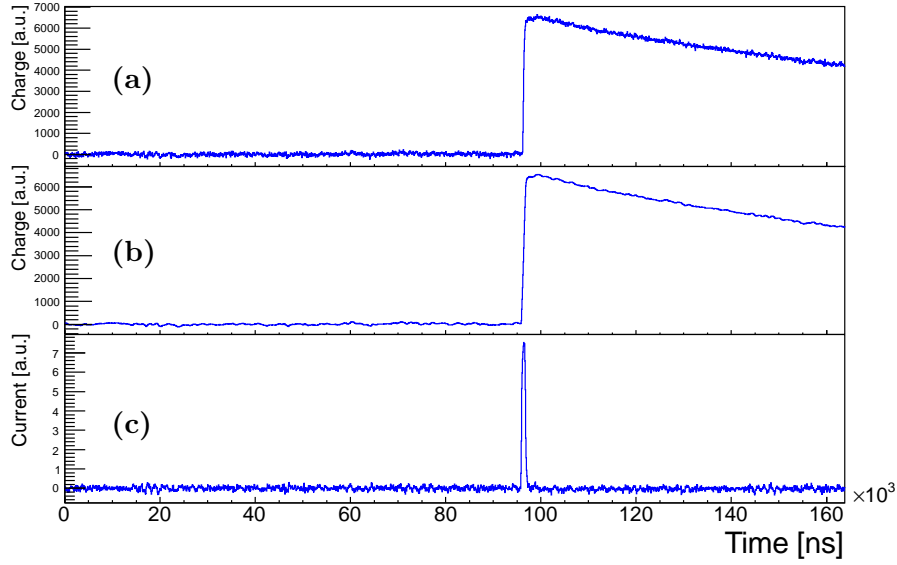


Figure 1. An example of a transform chain: (a) Original waveform (charge pulse); (b) Waveform processed with a 200-ns moving average filter to reduce the noise; (c) Output of the MGWFDerivative transform applied to the waveform (b), which yields the current pulse.

the GELATIO and GAT analysis modules implementing the waveform analysis are built as chains of MGDO transforms, thus favoring the re-use of the code and avoiding unnecessary duplication.

Although the specific applications by the MAJORANA and GERDA experiments drove the design and the development of the toolkit, the MGDO libraries, and in particular MGWaveform and its transforms, are generic enough to be applicable beyond the context of Germanium-based neutrinoless $\beta\beta$ decay experiments. It could be of potential interest for other low-background experiments from the perspective of setting up a standard and portable format which is suitable for the sharing and the inter-exchange of data and information.

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